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SMALL TURBINE ENGINE AUGMENTOR

Phase I - Preliminary Design Studies of Afterburner and Duct-Burner Configurations.

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NOTICE

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Several candidate afterburner and duct-burner concepts were evaluated during Phase I. The evaluation procedure included assessing engine and augmentor performance when integrated with airframe and mission data available from ATCM potential contractors. From the candidates analyzed, two configurations were chosen for further design evaluation in Phase II.

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SUMMARY

Several candidate afterburner and duct-burner concepts were evaluated. The evaluation procedure included assessing engine and augmentor performance when integrated with airframe and mission data available from ATCM potential contractors. From the candidates analyzed, two configurations were chosen for further design evaluation.

Of the several augmentor concepts screened, the conventional flameholder with mixer-nozzle and the partial-swirl augmentor were determined to produce the highest combustion efficiency with the least impact on the size or performance of the core engine. These two designs were therefore selected for detail analysis.

Two engines were evaluated for use in augmented cruise missiles. The lower-bypass-ratio engine was selected because of its smaller diameter, similarity to the Boeing ALCM-L engine, and greater suitability for augmentation.

The effect of using JP-10 and RJ-6 fuels was predicted to be small, but carbon-slurry fuel will require extensive modifications to the fuel manifold.

A

PREFACE

The Small Turbine Engine Augmentor Program is being conducted by the Garrett Turbine Engine Company, a division of The Garrett Corporation, for the Air Force Wright Aeronautical Laboratories, under Contract F33615-80-C-2001.

The program is being conducted under the direction of Mr. Elmer Buchanan, Project Engineer, AFWAL. The Garrett Program Manager and Principal Investigator are Mr. T. W. Bruce and Dr. H. C. Mongia, respectively. Key contributors to the program are Mr. T. E. Kuhn, who is responsible for the augmentor detailed Aero/Thermo analysis, design, and development testing; and Mr. J. V. Davis, who conducts the airframe integration and engine systems studies.

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1.0 INTRODUCTION

This document presents the Interim Technical Report for the Small Turbine Engine Augmentor Program.

The objective of this program is to conduct an exploratory development effort to provide technology for small turbine engine augmentors specifically oriented for Advanced Technology Cruise-Missile (ATCM) applications. The program consists of augmentor studies, concept selection, and the design, fabrication, and rig-test evaluation of a selected augmentor concept.

Phase I, which was recently completed and is the subject of this report, was to conduct preliminary design studies of promising afterburner and duct-burner configurations. The design performance constraints were established through engine/airframe consultation with ATCM contractors. System interface requirements were also established through airframe consultations. The anticipated fuel-injector effects, due to the projected use of JP-10, RJ-6, and carbon-slurry fuels, were established for the candidate designs. Both analytical and empirical design techniques were utilized in the study.

2.0 TECHNICAL DISCUSSION

The objective of Phase I of the USAF Small Turbine Engine Augmentor Program was to screen augmentor candidates in the 4.45kN thrust class (cruise-missile size) and provide preliminary design definition for two selected concepts. The selection of the two concepts was determined in conjunction with engine/airframe-integration studies.

In order to determine and assess the relative merits of candidate augmentor configurations (both afterburner and duct-burner), the initial tasks were to: (1) conduct a literature survey of available augmentor technology, (2) adapt and prepare available empirical models for use in preliminary design, and (3) define baseline cruise-missile engine configurations. The potential augmentor concepts were screened on the basis of their applicability to small turbine engines; specifically, advanced cruise-missile engines. Both conventional and high-intensity swirl afterburners, as well as duct burners, were studied. The most promising concepts were parametrically evaluated using empirical models and Garrett-derived analytical models. The predicted augmentor performance for each candidate was used to generate augmented engine performance when matched with the engine best suited for the mission and cycle requirements. From this analysis, the best two augmentor concepts, as well as engine configurations, were selected for final analysis and design. In addition, a preliminary analysis of the effects of using JP-10, RJ-6, and carbon-slurry fuels was performed.

2.1 Baseline Cruise-Missile Engines

Recent advanced cruise-missile studies have indicated that a long-range, low-signature vehicle cruising at subsonic speeds and

low altitudes can penetrate current and projected threats. Penetration survivability, however, has been shown to be improved by the addition of some form of thrust augmentation, used for either low-level supersonic terminal-dash capability or for maneuverability at subsonic Mach numbers (jinking). The selection of the optimum engine/augmentor system for a particular vehicle installation requires detailed engine/airframe integration.

Common to all engine concepts under consideration that employ augmentation are the requirements that the concepts minimize fuel consumption at cruise power settings and minimize engine diameter. Vehicle gross weight and range are extremely sensitive to these requirements. The minimum-diameter requirement tends to drive the engine towards a lower bypass ratio than would be selected on an independent basis.

Based upon mission analyses conducted with the Boeing Company, the cruise-missile engine will be subsonically operated at a specified percentage of military thrust for 80-percent of the mission duration in order to provide sufficient dry thrust for terrain following. This mission, which is supported by the McDonnell Douglas Astronautics Company (MDAC) and the Corvair Division of General Dynamics (GDC), influences the engine fan pressure ratio selection, and hence bypass ratio. Additionally, the engine should be optimized for low fuel consumption at the predominant specified percentage of military thrust.

The maneuvering mission was selected as the basis for augmentor selection considerations. The augmentor requirements for this mission are considered to be consistent with the technology of the proposed advanced engines (1983 to 1985 technology level). The supersonic dash mission was considered to have augmentor and system requirements that would be consistent with a 1990 to 1995

technology level. The manuevering mission consists of a long range subsonic cruise with jinking maneuvers, as necessary for threat avoidance. The augmentor is in the dry mode for cruise and in the augmented mode for jinking. An augmentation ratio of 2.0 is required for the maneuvering mission for jinking. The augmentor temperature rise during the augmented mode is 1144K.

The baseline Garrett engine that was initially evaluated at GDC is the ETF Model 1050-12. This engine is a low (1.1) bypass ratio, two-spool turbofan, and is well suited for an afterburner. A duct burner would not provide enough augmentation ratio due to the low-bypass-ratio level of this engine. Subsequent discussions with GDC resulted in the selection of higher bypass ratios than that of the ETF Model 1050-12. An engine bypass ratio between 1.5 and 2.5 provides acceptable range characteristics, and also offers lower IR signatures than the ETF Model 1050-12. Consequently, two engines were used for engine/airframe integration efforts in order to select the optimum engine-augmentor configuration, the ETF Models 1050-15B and the 1050-7B. Uninstalled, dry engine performance characteristics for these two engines are given in Table 1. Selection of the optimum engine-augmentor required additional engine/airframe integration efforts, and will be discussed in Paragraph 2.7.

2.2 Empirical Augmentor Model Description

An empirical model was adapted to calculate combustion efficiency and pressure loss for an afterburner with flameholders.

For an initial design, only the desired temperature rise, inlet airflow, temperature, and pressure are known. The augmentor fuel/air ratio required for a given temperature rise is a function of the combustion efficiency, which in turn, is influenced by the fuel/air ratio. The solution is an iterative

process, with the value of fuel/air ratio being assumed and then corrected until the calculated temperature rise matches the desired value. The calculation of combustion efficiency from the selected inlet conditions, afterburner length, and fuel/air ratio follows the work by Petrien et.al. (Reference 1), as described in the following paragraphs.

TABLE 1. ETF MODEL 1050 ENGINE COMPARISON PRELIMINARY INSTALLED DATA DRY AFTERBURNER MACH = 0.7, SEA-LEVEL STANDARD.

ETF Model 1050	-15B*	-7B
Specific Thrust, s	32.8	24.8
Fan Pressure Ratio	2.2	1.85
Cycle Pressure Ratio	16	16
Turbine Inlet Temperature, K	1533	1533
Bypass Ratio	1.37	2.36

*B designation indicates the particular engine cycle has been configured for an afterburner.

The maximum laminar flame speed at the afterburner inlet conditions, Su_{max}, is given in Reference 1 as:

$$Su_{max} = 2.05 \times 10^{-4} \sqrt{X_{O_2} \frac{T_2^{2.5} T_f^4}{(T_f - T_2)^3} \mathrm{EXP}(-13222/T_f)}$$

where: X_{O_2} = mole fraction of oxygen in afterburner inlet air

T_2 = static temperature at flameholder, K

T_f = stoichiometric flame temperature, K

The flame speed, Su, at the afterburner inlet conditions and fuel/air ratio is as follows:

$$Su = \frac{Su'}{0.4023} Su_{max}$$

where: Su' = Laminar flame speed of propane in air at reference inlet conditions as a function of fuel/air ratio, m/s

Su_{max} = maximum laminar flame speed as previously described, m/s

The combustion efficiency is a function of the correlation parameter B, as shown in Figure 1. Parameter B is given by Reference 1 as:

$$B = \frac{L}{1.094} (45.7/V_1)^{0.6} (P_1/1.013x10^5)^n (Su/0.628)^{0.6} + \Delta L/0.914$$

where: L = afterburner length, m

V_1 = velocity before flameholder, m/s

P_1 = static pressure before flameholder, Pa

n = pressure exponent as function of flame spreading distance

ΔL = length correction, as function of flame spreading distance, m

From the calculated efficiency and assumed fuel/air ratio, the temperature rise is calculated using a Garrett subroutine which includes the effects of vitiation and dissociation. The calculation procedure is repeated until the temperature rise is the required value for the desired augmentation ratio.

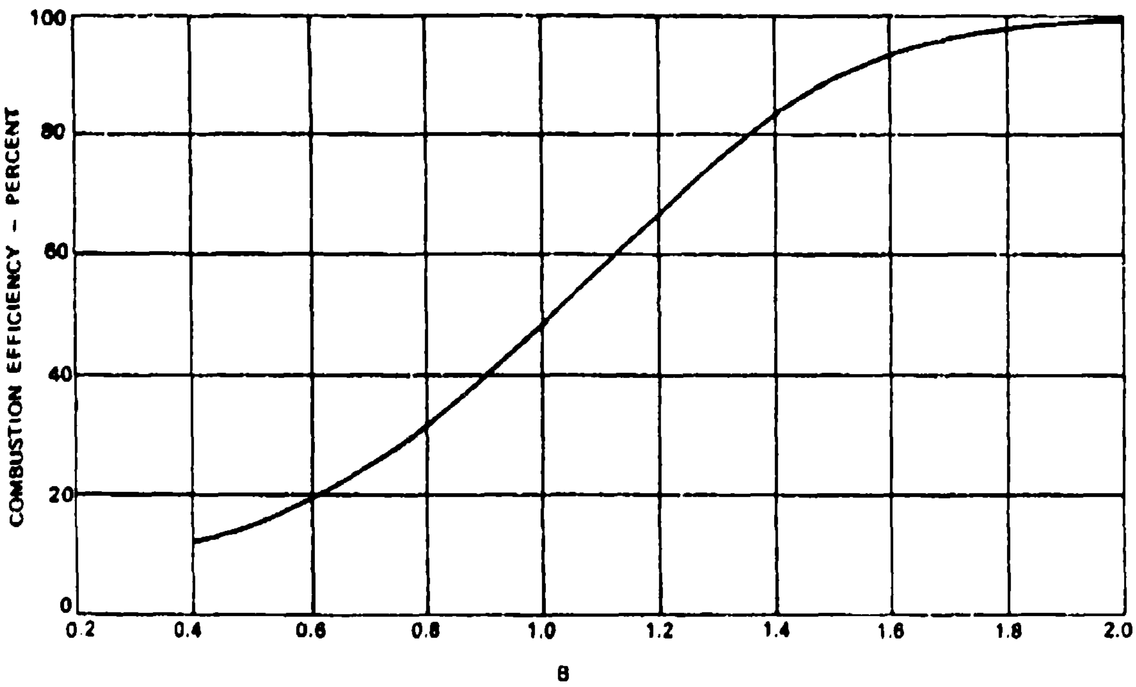


Figure 1. Combustion Efficiency Correlation Parameter B.

The program also computes the dry and momentum pressure losses by assuming each loss occurs separately and adding the two losses together. The error involved in not treating the losses together is considered to be small. Standard expressions for friction, diffusion, and momentum losses are used. Flameholder blockage losses are taken from Kumar (Reference 2), and the equation is as follows:

$$C_D = 4\ B^2\ (2-B)\ \sqrt{\sin\ \ /2}/(1-B)^2$$

where: C_D = loss co-efficient

B = flameholder geometric blockage

θ = included angle of V-gutter

2.3 Fuel-Injection Model Description

A fuel-injection computer program was written to calculate the penetration, spread, and droplet size of liquid jets for cross-stream injections into high-velocity airflows. The expression for droplet size, termed the Sauter mean diameter (SMD), is taken from Ingebo (Reference 3):

$$SMD = 3.9\ d_o\ (W_e/R_e)^{0.25}$$

where: d_o = orifice diameter, same units as SMD

W_e = $\sigma/\rho_a d_o V_a^2$ Weber number, dimensionless

R_e = $d_o V_a/\nu$ Reynolds number, dimensionless

σ = fuel surface tension

ρ_a = air density

V_a = air velocity

ν = fuel kinematic viscosity

Ingebo varied the liquid velocity from 24 to 61 m/s and found no significant change in SMD.

The expression for jet penetration (perpendicular to airflow direction) was taken from work done at AFAPL (Reference 4), and is as follows:

$$Y/d_o = 2.1 \sqrt{q} \; (x/d_o)^{0.27}$$

where: Y = penetration distance

q = $\rho V^2/\rho_a V_a^2$

ρ = fuel density

V = fuel velocity

X = axial distance downstream

This expression yields penetration close to the predictions of Schitz and Padhye (Reference 5), but only for large values of x/d_o (>100). The range of interest of x/d_o is from 75 to 150 for this design study, so the discrepancy between the two expressions is typically small. The following expression for the spread or fanning out of the jet as it moves downstream is also extracted from Reference 4.

$$Z/d_o = 6.95 \; (x/d_o)^{0.33}$$

where Z = spread of jet

2.4 Conventional Afterburner Evaluation

The following parameters are evaluated for their effect on augmentor performance in both the high- and low-bypass-ratio engines: (1) fuel staging zone size, (2) flameholder geometry, (3) fuel injection system, and (4) inlet Mach number.

The desired temperature rise of the augmentor of the ETF Model 1050-15B engine at an augmentation ratio of 2.0 is 1150K. Assuming ideal conditions, the overall fuel/air ratio is only 0.028, which is below or near the blowout fuel/air ratio of most conventional afterburners. Therefore, the combustion process for a conventional-flameholder afterburner for small turbine engines must be confined to only a portion of the airstream. Increasing the local fuel/air ratio provides margin over the lean-blowout limits and improves combustion efficiency. In addition, augmentor liner life can be significantly improved by providing a cooler air film in contact with the liner surfaces. However, high temperature rises in the burning portion of the airstream produce high Rayleigh (heat addition) losses. Also, if there is not sufficient mixing between the combustion gases and the bypass air, the exhaust-nozzle thrust coefficient may decrease as much as 2 percent (assuming no mixing). Therefore, there is an optimum amount of air which should be allowed to bypass the combustion process.

The effect of the amount of bypass air on combustion efficiency, local fuel/air ratio, and pressure drop is shown in Figure 2 for the ETF Model 1050-15B. A value of 20-percent bypass air was chosen because the efficiency and lean-blowout margin are adequate, and higher bypass percentages would decrease the mixedness of the exhaust gases and lower the nozzle thrust. A value of 20 percent was also found to be optimum for the ETF Model 1050-7B afterburner.

From experience and theoretical considerations it is known that little improvement in combustion efficiency is achieved beyond 35-percent flameholder blockage. A number of flameholder configurations were evaluated including single annular gutter, double annular gutter, and a single annular gutter with finger-gutter arrangement. Experience on large afterburners has shown that V-gutter width and approach Mach

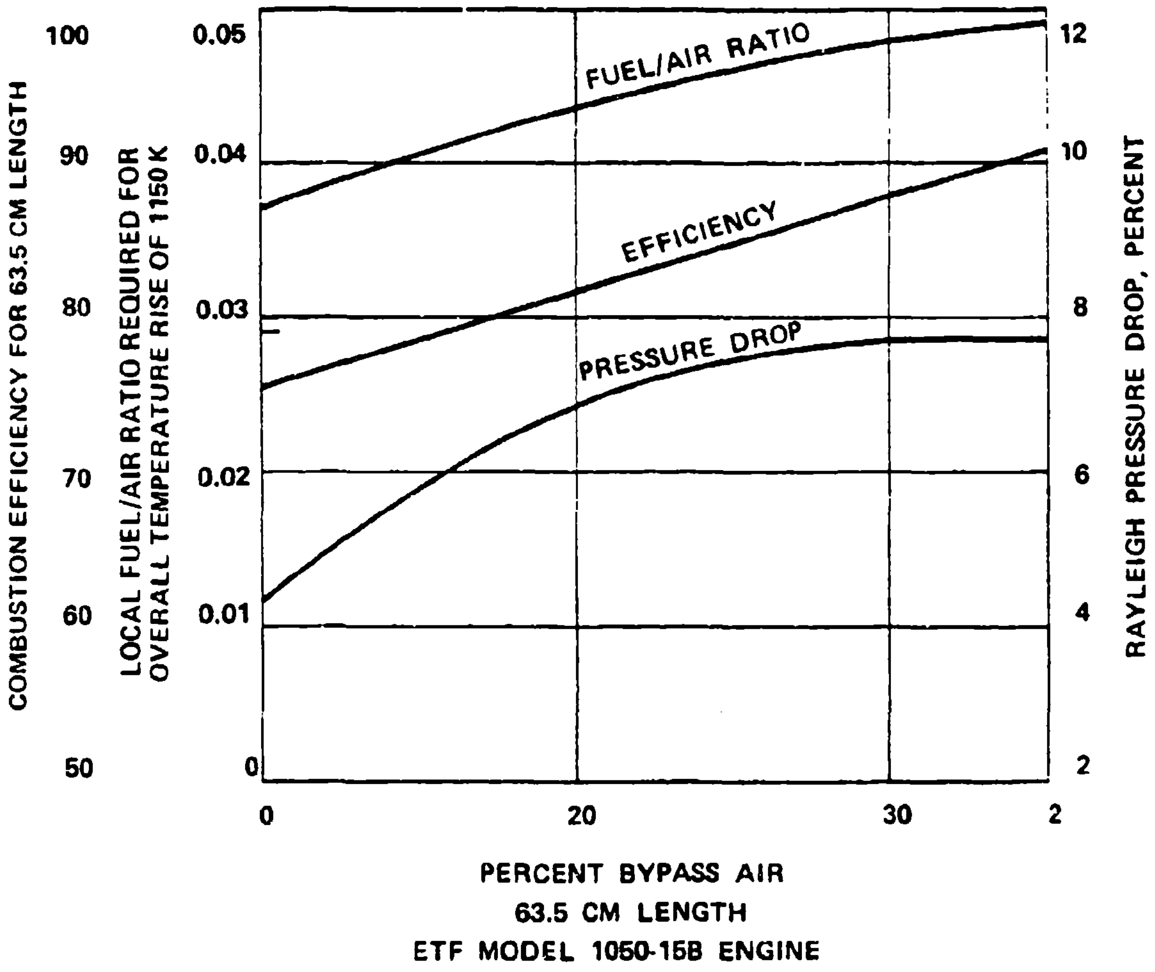


Figure 2. Effect of Bypass Air on Augmentor Performance.

number are closely related in regard to lean blowout and combustor efficiency. For given inlet conditions, it directly related to the time the fresh unburned fuel-air mixture stays in contact with the hot ignition gases from the flameholder wake. With everything else remaining the same, the minimum allowable width is directly proportional to the approach Mach number. The majority of the V-gutters used on large afterburners have widths of approximately 3.8 cm, with a few as low as 3.2 cm for the lower end of the approach Mach number. With still lower Mach numbers, such as in a duct burner designed by G.E. under NASA sponsorship (Reference 6), V-gutters with 1.9 cm width have been successfully used.

For the preliminary study phase of the present program, a minimum allowable width of 3.2 cm was considered acceptable. Detailed analysis and element testing (if undertaken) during Phase II will establish criteria for a minimum acceptable gutter width in regard to lean blowout, combustion efficiency, and dry pressure loss.

A single annular gutter with 35-percent blockage, located midway between the center and wall of the afterburner, was predicted to have a low combustion efficiency and a high lean blowout fuel/air ratio. A two-annular-gutter configuration with 3.2 cm gutter width gave blockage more than 35 percent, and therefore was dropped from further considerations.

A majority of initial design iterations were therefore done on the flameholder configuration incorporating a single annular gutter with radial fingers. The effect of the radial-finger design features, such as the number and the split between the inner and outer flow streams, height, width and swept back angles in the afterburner performance were evaluated qualitatively and quantitatively, where possible. Figure 3 presents an

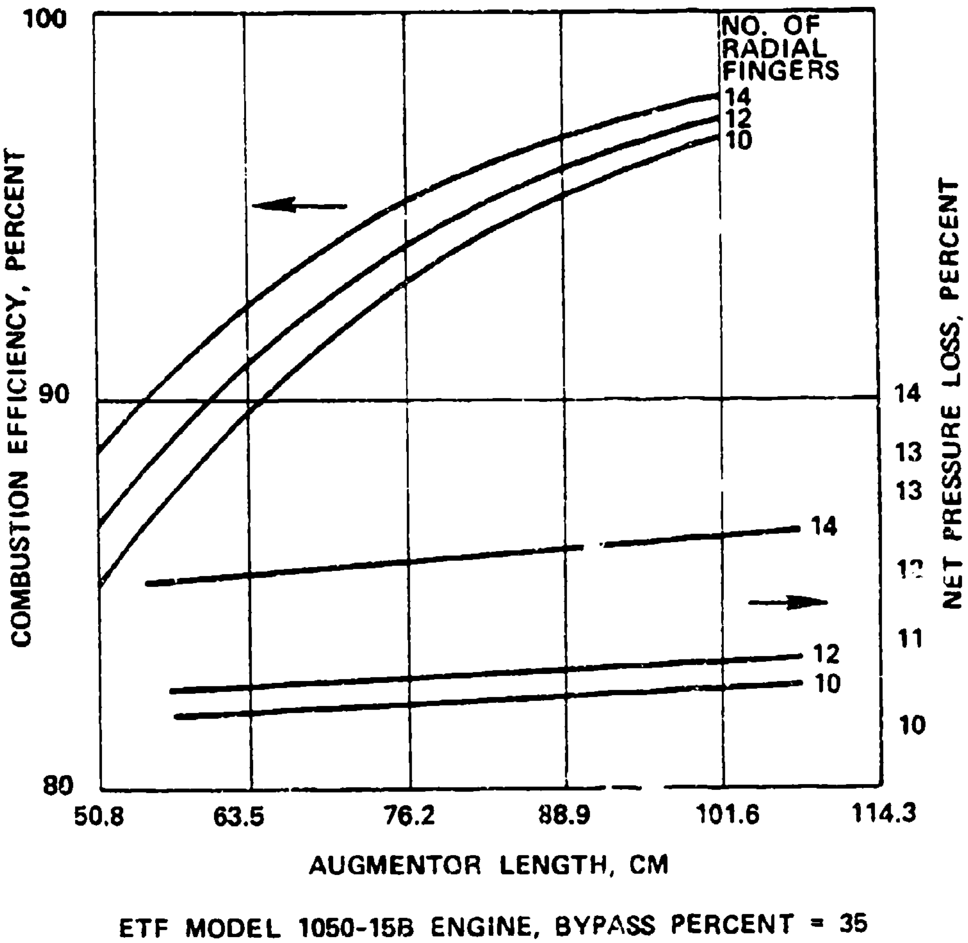


Figure 3. Effect of Flameholder Geometry on Efficiency and Pressure Loss.

example of this phase of the activities. The combustion efficiency and pressure losses were calculated empirically as influenced by the number of radial fingers. Although the combustion efficiency is shown to improve monotonically with the increasing number of radial fingers, a trade-off needs to be made to keep the pressure drop within an acceptable limit. For the ETF Model 1050-15B augmentor, Figure 3 indicates that optimum performance can be achieved by using a single annular gutter with 12 radial fingers.

A typical preliminary design iteration for the fuel-delivery system consists of the design of spray rings/bars including the number and sizes of the orifices, the attendent fuel-pressure drop, and penetration and spreading of the spray plumes. Many considerations including installation, structural durability, and blockage must be taken into account in order to select any of the three types of fuel-delivery arrangements: spray rings, spray bars, and a combination of rings and bars. A limited number of layout sketches for the small turbine engine augmentor indicated that for a large number of orifices, spray rings are preferable; whereas, for less than 20 orifices, spray bars are more desirable. As explained in the following paragraphs, the ETF Models 1050-7 and -15 afterburner require 108 and 83 orifices, respectively. Therefore, spray rings were selected for application in the small turbine engine augmentor.

The size and the number of orifices is decided by a number of design requirements including fuel distribution and minimum and maximum fuel-pressure drops. The number and size of the orifices should be a maximum to increase the spread of the fuel jets and decrease the circumferential variations in local fuel/air ratio. The number and size of the orifices should be minimized for fuel pressure, fuel droplet size, and penetration considerations. The calculated effect of the orifice diameter on fuel-pressure drop, droplet size, and spray penetration and speed is shown in Figure 4. A series of such curves was generated for

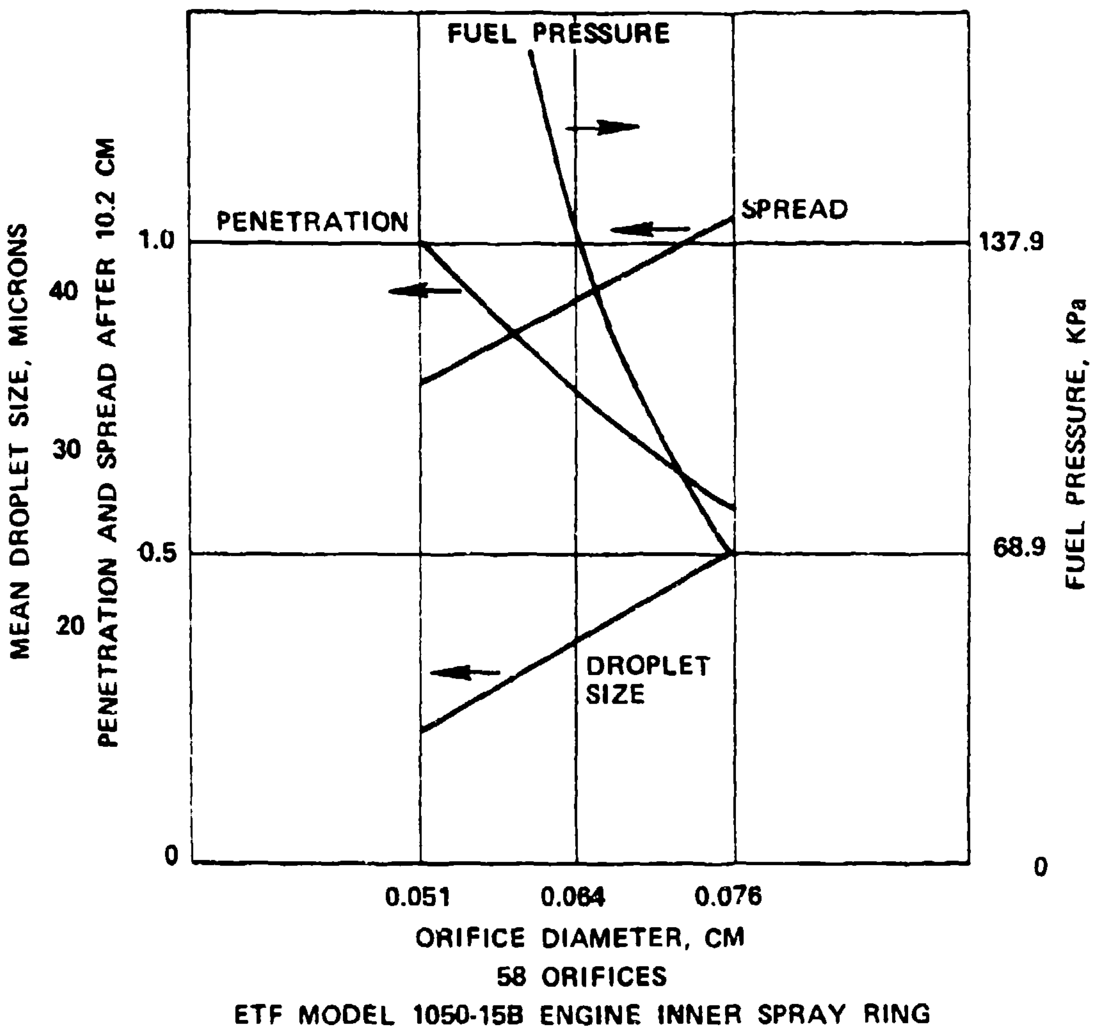


Figure 4. Spray-Ring Design Parameters as Function of Orifice Diameter.

different numbers of orifices. These calculations showed that the smallest orifice size was not necessarily the best for achieving a uniform fuel-air distribution. An orifice diameter of 0.53 mm was found to be optimum, and is recommended for further evaluation.

The axial location of the spray rings is decided by many considerations, including spray penetration and spread, degree of prevaporization required, and rumble. A preliminary study of the axial position of the fuel spray rings was therefore conducted by using the 2-D augmentor model. The ETF Model 1050-15B augmentor was modeled as shown in Figure 5 for the plane in between the radial fingers. The axial direction (X-nodes) continue out to 61 cm from the flameholder. Two cases were run with the 2-D model: (1) the 10.2 cm injection length with pilot burner at the core as shown in Figure 5, and (2) with the flameholder moved to within 5.1 cm of the spray rings and the pilot burner removed. The predictions of combustion efficiency for the two different lengths from the spray ring to the flameholder are given in Figure 6 and shows that the combustion efficiency was considerably reduced with the 5.1 cm injection length. More analytical study is planned. A computer plot of the fuel/air ratio profiles of the ETF Model 1050-15B augmentor with a 10.2 cm injection length is shown in Figure 7. The fuel/air ratios near the core are nearly three times the values on the outside of the V-gutter, resulting in low combustion efficiencies near the core (as shown in Figure 8). The fuel flow to each spray ring should therefore be adjusted, and optimum split can be obtained by using the 2-D model.

The approach Mach number of the initial high-bypass-ratio engine afterburner (ETF Model 1050-7 configuration) was maintained at 0.23 in order to stay within the engine envelope. Since this is higher than the Mach number used in larger afterburners, the predicted combustor efficiency of the ETF Model 1050-7 afterburner was lower than the -15 configuration (as

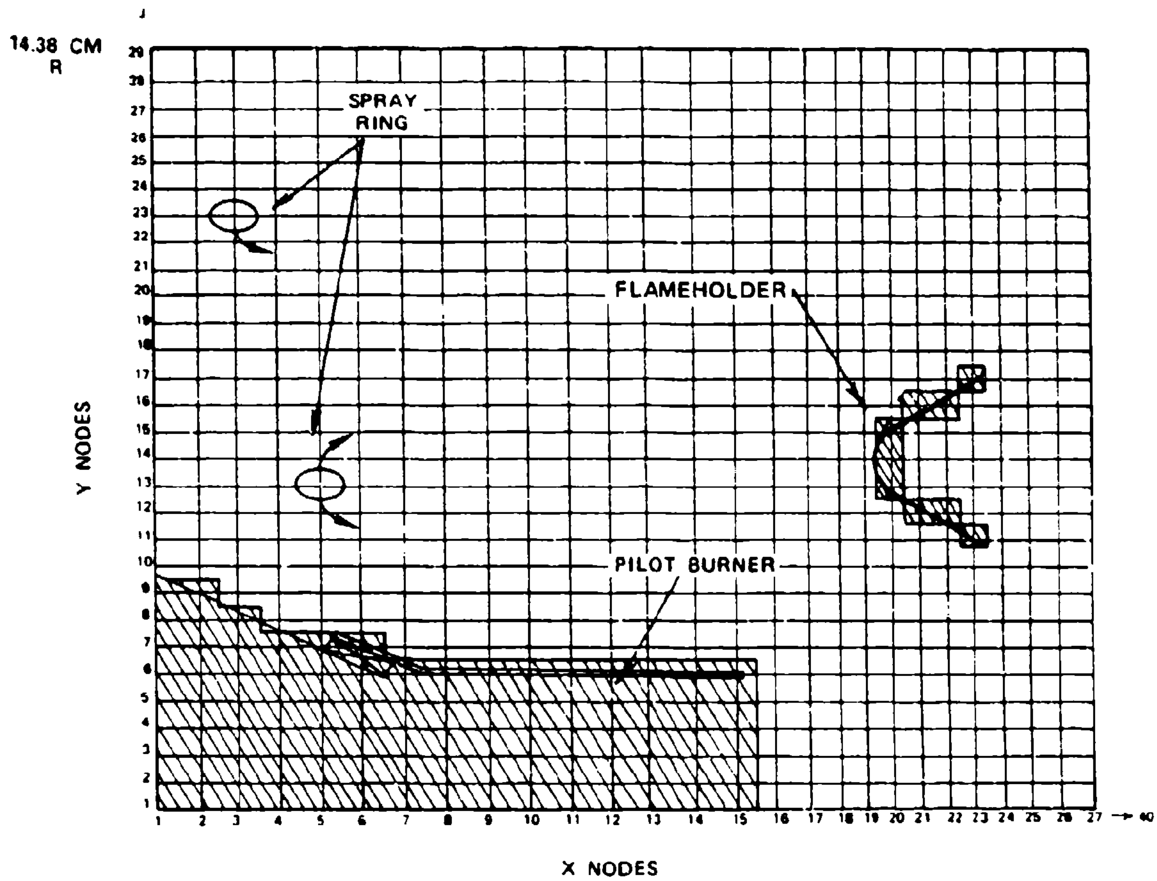


Figure 5. 2-D Flameholder Simulation, ETF Model 1050-15B Augmentor.

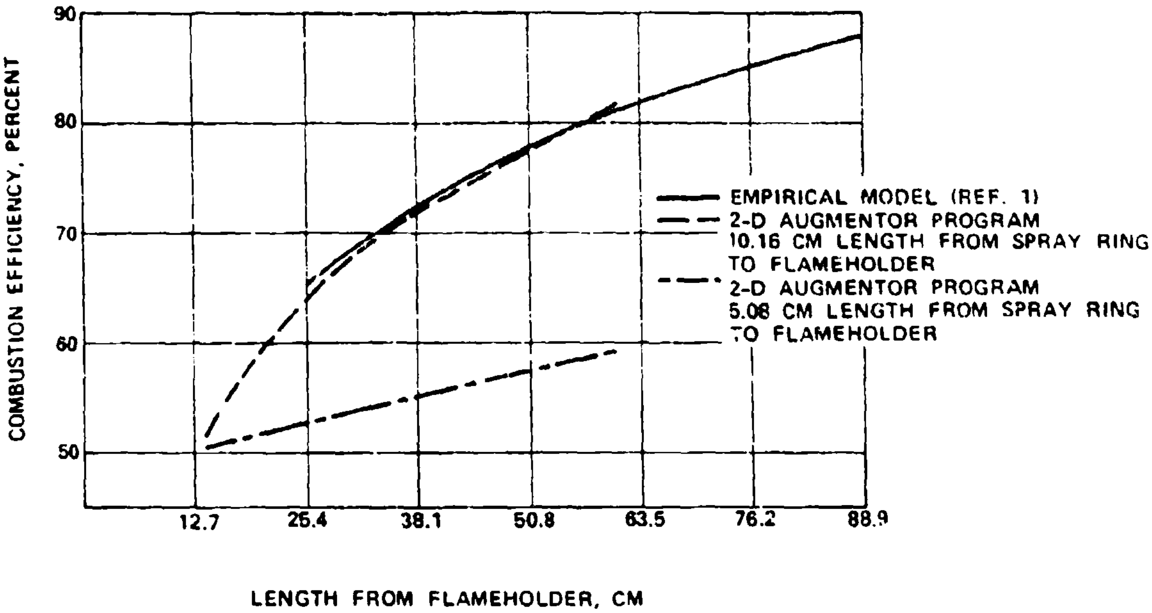


Figure 6. Predicted Combustion Efficiency of Flameholder, ETF Model 1050-15B Augmentor.

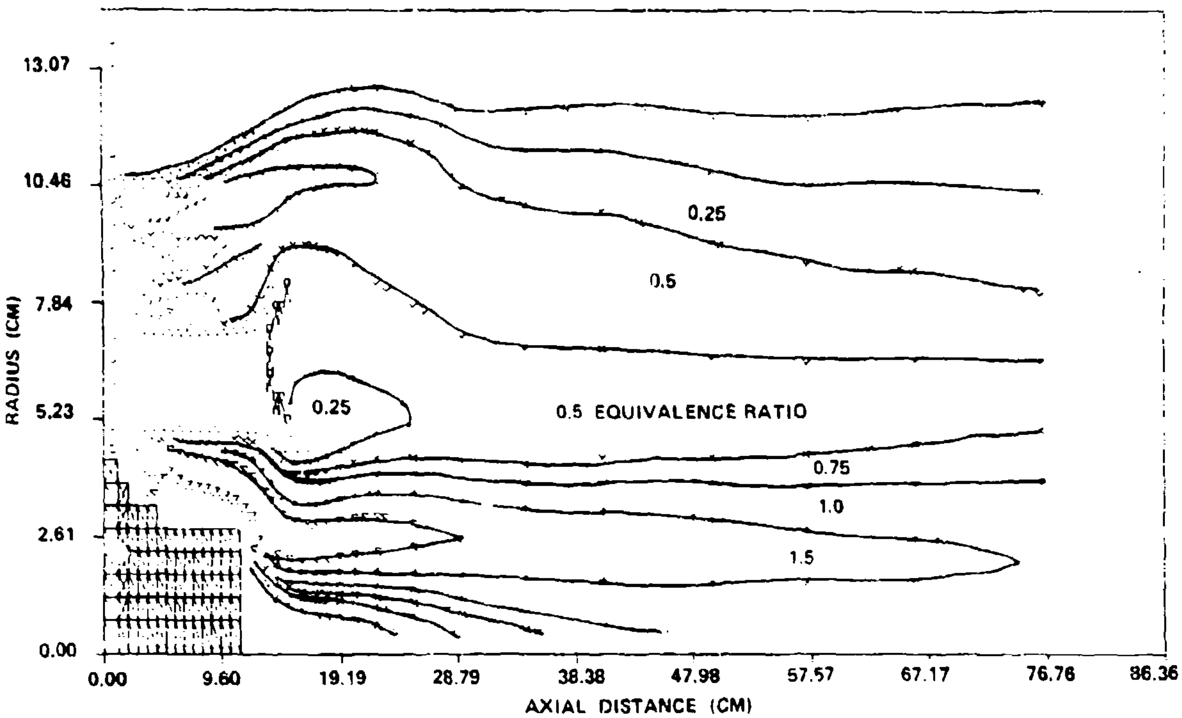


Figure 7. Equivalence Ratio In Between Radial Fingers, ETF Model 1050-15B Conventional Afterburner.

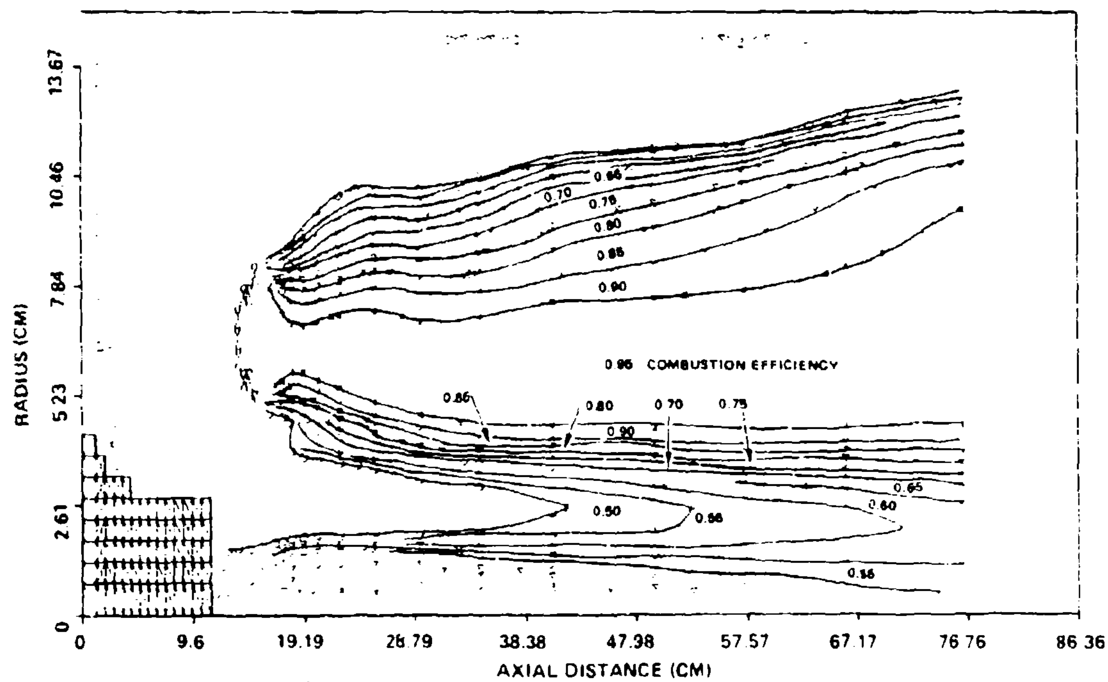


Figure 8. Predicted Combustion Efficiency Isopleths In Between Radial Fingers, ETF Model 1050-15B Conventional Afterburner.

shown in Figure 11 to be discussed later). However, a 3-percent gain in combustion efficiency was predicted by decreasing the approach Mach number to 0.2.

Based on the preliminary results of the design studies outlined in the previous paragraphs, the configurations recommended for the ETF Models 1050-15 and -7 are shown in Figures 9 and 10, respectively. The location of the pilot shown has not been optimized to ensure soft lightoff. As shown here, the ETF Model 1050-7B engine augmentor configuration has been scaled up from the low-bypass-ratio engine. However, an additional row of orifices was added to the outer spray ring in order to provide a uniform fuel-air distribution over the larger airflow area.

The combustion-efficiency predictions for both engine configurations are given in Figure 11. The low-bypass-ratio engine efficiencies greatly exceed those of the ETF Model 1050-7B engine because of the higher inlet air temperatures. The pressure losses for both augmented engines are listed in Table 2. The wet and dry losses lie within the range of experience for conventional augmentors.

TABLE 2. AFTERBURNER PRESSURE LOSSES

Afterburner Pressure Loss, Percent

Configuration, ETF Model 1050	Wet	Dry
-15B Flameholder	9.8	4.2
-15B Partial-Swirl	8.7	2.2
-7B Flameholder	7.9	4.2
-7B Partial-Swirl	9.9	2.7
-7B Duct Burner	13.3	5.3

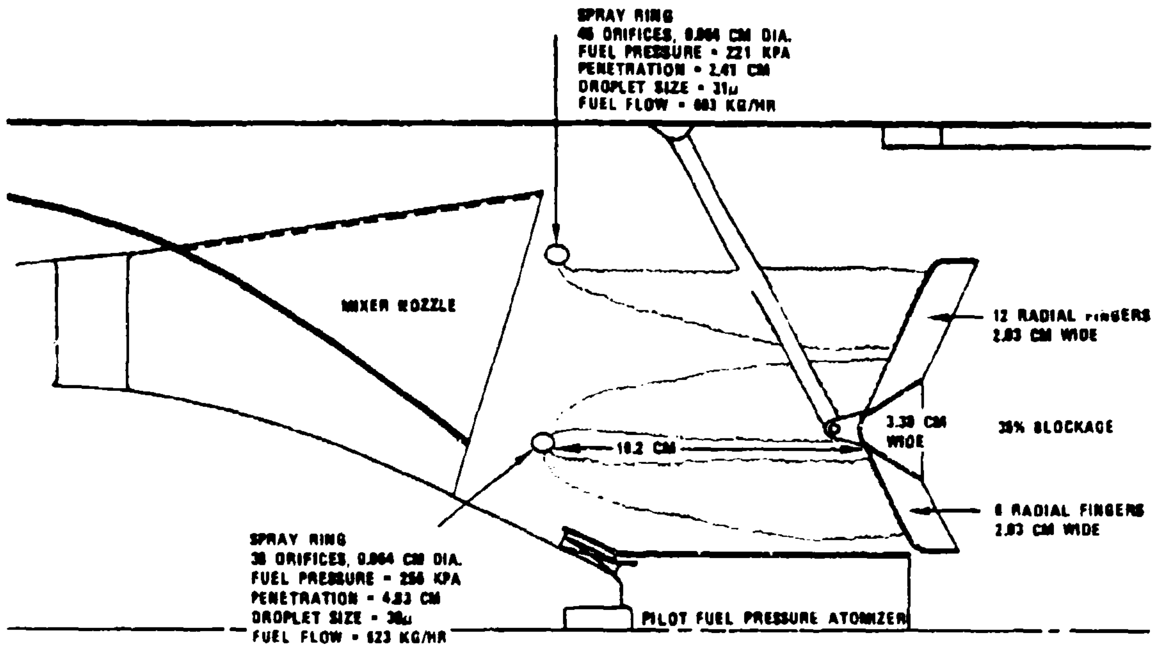


Figure 9. ETF Model 1050-15B Conventional Afterburner.

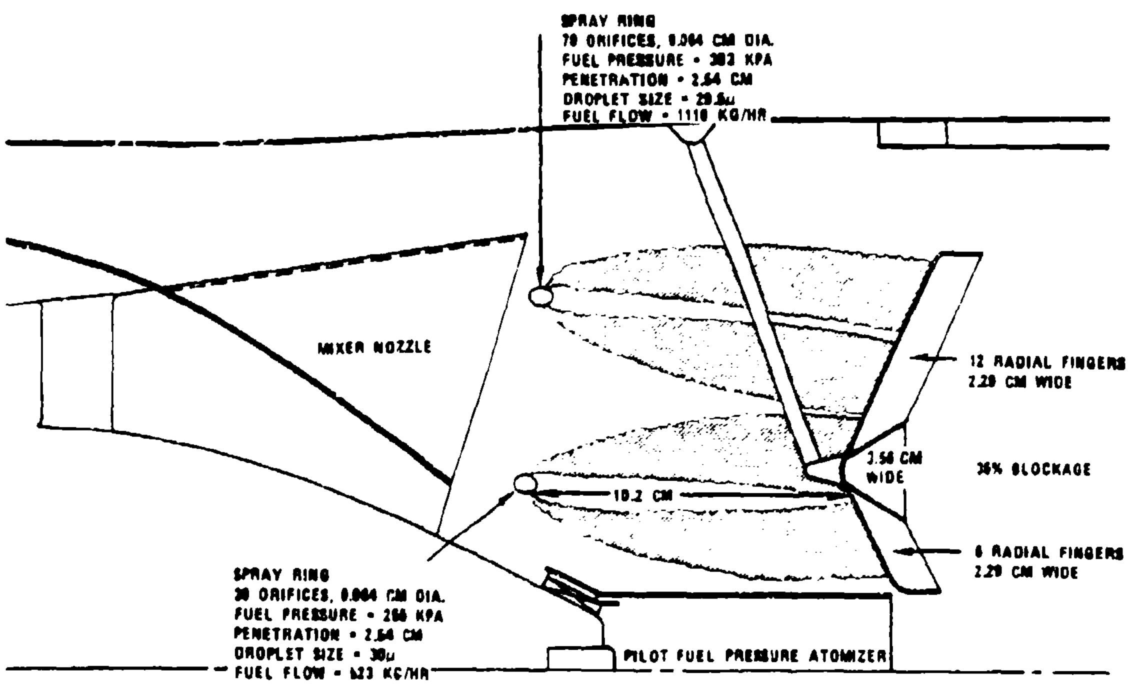


Figure 10. ETF Model 1050-7B Conventional Afterburner.

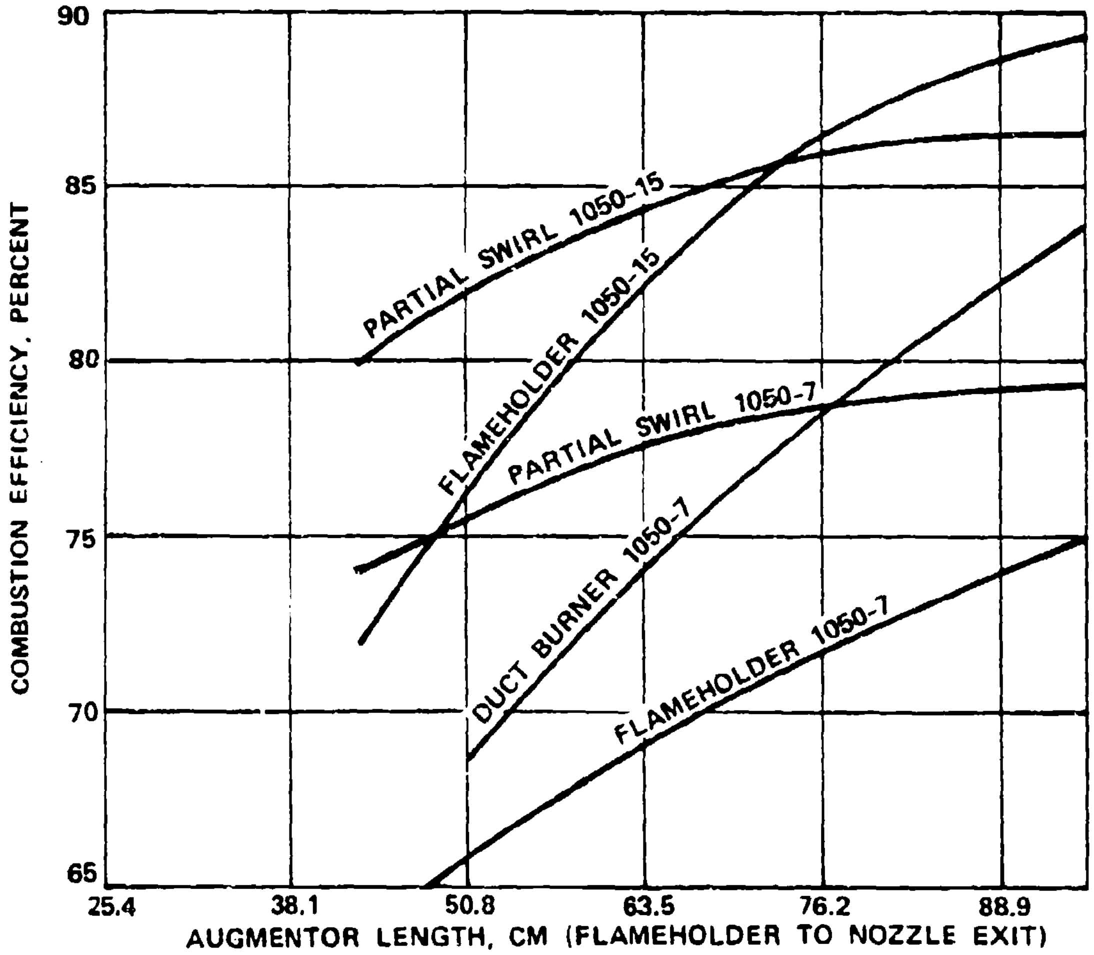


Figure 11. Empirically Predicted Combustion Efficiencies of Different Augmentor Configurations.

2.5 Duct-Burner Configurations

The bypass ratio of the ETF Model 1050-15B engine is too low to produce adequate augmentation with a duct burner. A duct burner was therefore designed only for the high-bypass-ratio engine. A parametric evaluation, similar to that conducted on conventional afterburners, was performed to determine the amount of air bypassing the augmentor, the number and sizes of the fuel orifices and radial V-gutters, and the size of the pilot. The width of the radial fingers was held to the minimum that has been successfully tested (1.9 cm). The small width is required to limit the flameholder blockage and flame-spreading distance. A full-annular pilot is used to ensure adequate ignition to prevent fan surge. The size of the pilot was determined from the conflicting requirements of combustor volume and engine diameter. From Garrett combustor experience, a channel height of 2.5 cm was considered to be the minimum. The final configuration is shown in Figure 12. It was found that a substantial amount (37.5 percent) of the fan air must be bypassed around the V-gutter to achieve acceptable efficiency at the low fan air temperature. The resulting high fuel/air ratio in the duct burner produces high Rayleigh (heat addition) pressure losses (as shown in Table 2). The dry pressure loss is somewhat higher because of friction losses through the long, small channel height passages shown in the engine drawing of the duct burner, Figure 13.

The duct burner adds 15.8 cm to the engine diameter, which is a 30-percent increase. For this reason and others (such as low combustion efficiency) the duct burner is not considered an acceptable alternative to a conventional afterburner.

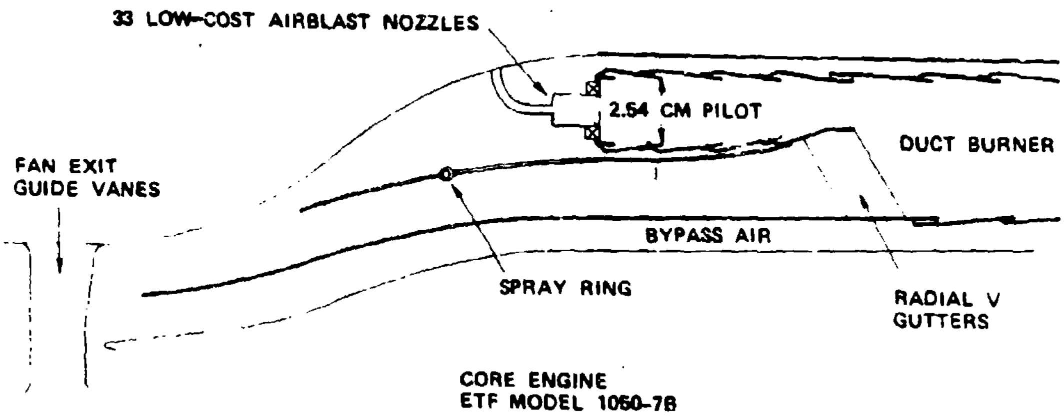


Figure 12. Conventional Duct-Burner Design.

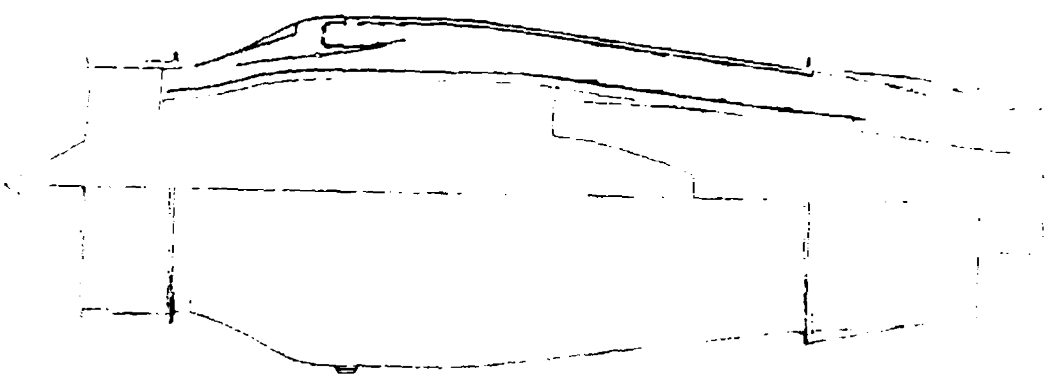


Figure 13. ETF Model 1050-7 Duct Burner.

2.6 High-Intensity Afterburner Configurations

2.6.1 Vorbix Augmentor

High combustion efficiencies have been achieved with a vorbix (vortex burning and mixing) augmentor utilizing pairs of swirling jets to enhance the combustion intensity due to the centrifugal forces (Ref. 7). The augmentor is comprised of a pilot, which vaporizes the secondary fuel, and swirling high-velocity jets, which interact with the fuel-rich pilot discharge gases and produce rapid mixing and burning. The pilot was sized for the low-bypass-ratio engine augmentor, and the penetration of the secondary fuel inside the pilot burner was calculated using the empirical fuel-injection model previously described. The fuel penetration was predicted to be 7.6 cm because of the low gas velocities inside the pilot. The fuel would therefore impinge on the pilot wall and would not exit the pilot adjacent to the swirling jets. The fuel injectors were changed from simple orifices to pressure atomizers, and another Garrett fuel-injection model was used to predict the trajectory and vaporization rate of the fuel spray. Again, the fuel spray impinged on the pilot wall. Therefore, the vorbix design was not pursued further because the size constraints present severe problems in preventing fuel impingement on the pilot walls.

2.6.2 Swirl Augmentor

A swirl augmentor was designed based on the work by Clements on a single-stream swirl-augmentor test rig (Ref. 8). In this design, the turning portion of the turbine exit guide vanes was removed and swirl vanes were placed in the fan duct to swirl the inlet air up to 35 degrees. The resulting centrifugal forces greatly enhance the combustion efficiency by increasing the flame velocity. The flow is ignited by a full-annular combustor placed on the outside diameter of the augmentor so that the bouyancy

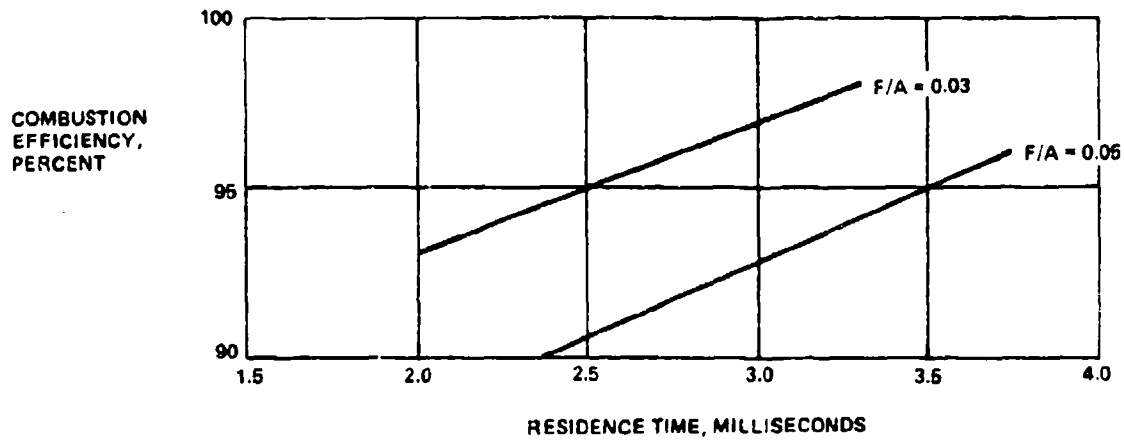
forces will displace the less dense pilot gases towards the center of swirl.

In order to predict swirl-augmentor efficiency, the 2-D model was correlated with dump-swirl afterburner data (Ref. 8). The measured effect of a change of 30 degrees of swirl was an increase in efficiency of 15 percent, but the model predicted only an 8-percent increase. Garrett-sponsored work on the model was conducted and the correlation was improved.

A swirl augmentor was designed with a 2.5 cm channel height pilot combustor (the minimum size considered practical) and modeled with the 2-D swirl model. The predicted combustion efficiency was extremely low (54 percent) for a length of 30 cm. The reason for the inefficiency is the 383K (ETF Model 1050-7B engine) to 405K (ETF Model 1050-13B engine) fan-discharge air temperature. Little combustion occurs in the fan air that flows between the hot core gases and the pilot, and the fan air interferes with the ignition of the core gases.

Because of the low efficiency of the swirl augmentor, a partial-swirl augmentor was then designed. Only the core gases were swirled. The pilot burner was placed adjacent to the core gases, which eliminated the separation of the hot core gases and pilot (which produced low efficiency in the full-swirl augmentor). The partial-swirl design also has the advantage of a higher nozzle thrust coefficient, compared to the full swirl, because of the lower amount of swirl in the exhaust nozzle.

The combustion-efficiency predictions for the swirling core gases were taken directly from the data by Clements (Reference 9). Augmentor combustion efficiency at different fuel/air ratios is plotted against the residence time of the reacting gases in Figure 14. These lines were used to predict the efficiency of the core combustion in the ETF Model 1050 augmentors, since the



	REFERENCE	TFE1050-7B	TFE1050-15B
SWIRL COMBUSTOR PRESSURE, KPA	239.2	240.6	280.6
TEMPERATURE, K	930	975	1007
AXIAL MACH NUMBER	0.255	0.34	0.29
SWIRL ANGLE, DEGREES	35	35	35
SWIRL FORCE AT PILOT, G'S	7×10^3	2.5×10^5	1.8×10^5

REFERENCE: CLEMENTS, T.R., "EFFECT OF SWIRLING FLOW ON AUGMENTOR PERFORMANCE, PHASE II FINAL REPORT", NASA CR-135024.

Figure 14. Swirl Combustor Efficiency Predictions.

data was taken at inlet conditions nearly equal to that of the present design study. The strength of the swirl force at the pilot, which is proportional to V_t^2/R, is greater for the ETF Model 1050 design than for the data by Clements because of the higher velocity and smaller radius. Therefore, the swirl angle of 35 degrees (investigated by Clements) could possibly be reduced.

Flameholders were placed in the fan air in order to achieve the desired augmentation of 2.0. The partial-swirl designs are shown in Figures 15 and 16 for the two engine configurations. The pilot burner will require 20 pressure atomizers inserted through the combustor dome. The three separate fuel manifolds and the annular combustor make the swirl design more mechanically complex that the conventional design. Most of the fuel is placed in the core gases where the efficiency is the highest.

The efficiencies predicted for the fan flameholders are low (60-75 percent) since all the combustion is taking place at an inlet air temperature of 394K, similar to the duct-burner design. However, the overall efficiency of the partial-swirl design is generally higher than the conventional design because of the high efficiencies of the core gas combustion. The partial-swirl augmentor efficiencies are compared to those of the conventional augmentors in Figure 11. The partial-swirl augmentors allow a reduction in augmentor length of 15.2 cm for the ETF Model 1050-15B, and 45.7 cm for the ETF Model 1050-7B configuration, when compared to the conventional augmentors with equal efficiencies. The pressure loss through the partial-swirl augmentors is approximately 2-percent (of the inlet pressure) less than the conventional designs (as shown in Table 2). This reduced pressure loss decreases the engine thrust specific fuel consumption (TSFC) 1 percent, and partially compensates for the lack of a mixer nozzle (which cannot be incorporated into the partial-swirl designs, but which is included in the conventional

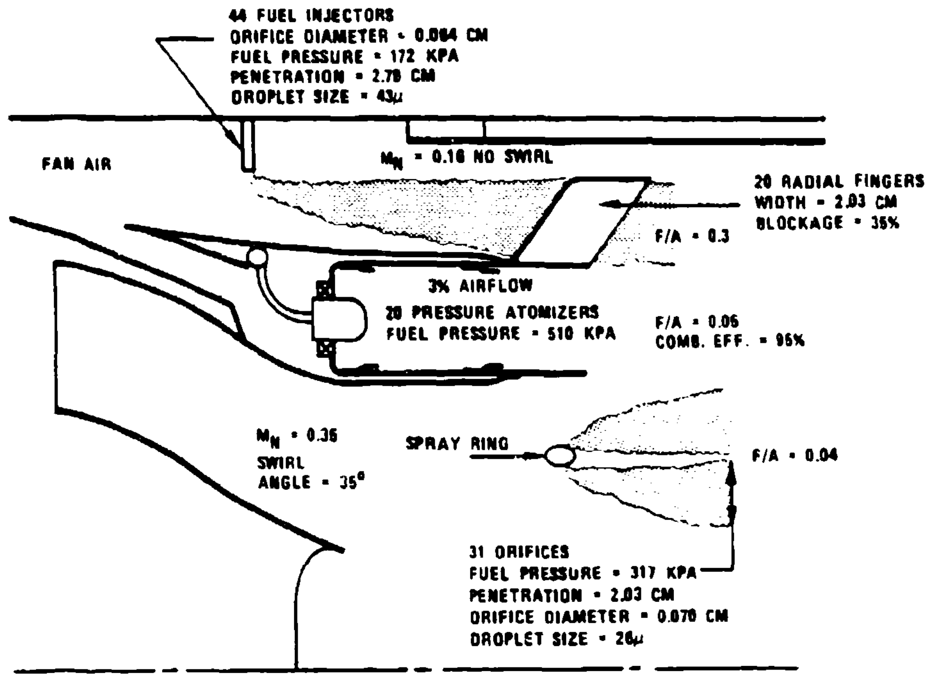


Figure 15. ETF Model 1050-15B Partial-Swirl Augmentor.

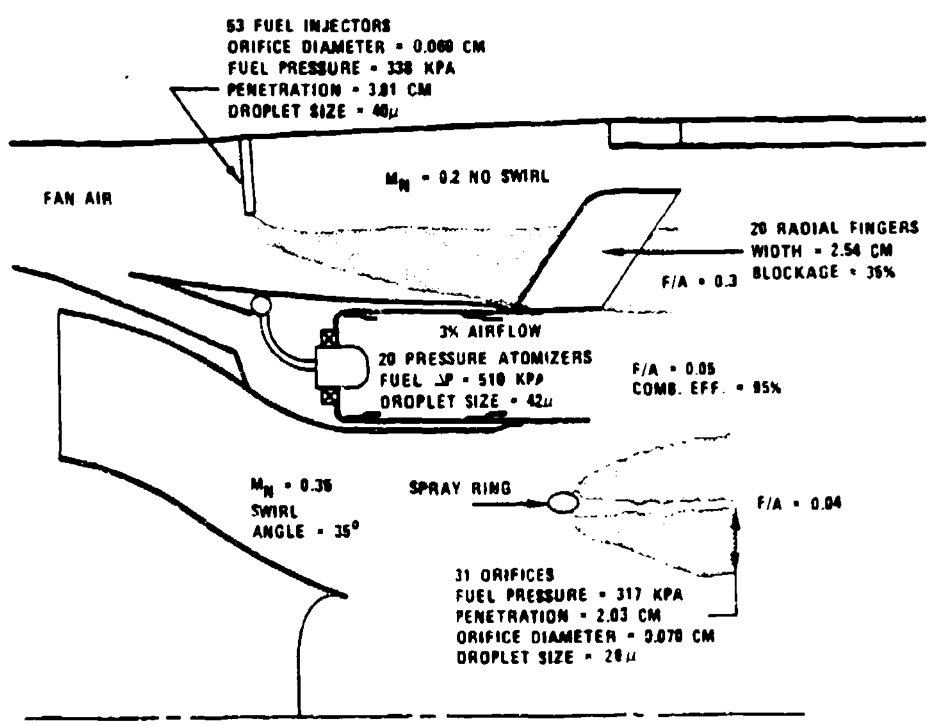


Figure 16. ETF Model 1050-7B Partial-Swirl Augmentor.

designs). The partial-swirl design can only utilize a mixer nozzle by inserting the swirl vanes downstream of the mixer nozzle, which is considered impractical. The effect on TSFC of swirl in the exhaust nozzle can be minimal if the swirl angle in the nozzle is limited to 10 degrees (Reference 9). This should be attainable with the partial-swirl design since less than half the air is swirled.

In order to achieve combustion efficiency in the fan airstream, the pilot and flameholders were replaced by swirl-can modules that have achieved high efficiencies in testing by NASA in large combustors (Reference 10), and in an augmentor rig (Reference 11). The conceptual drawing is shown in Figure 17. The design is greatly reduced in complexity, requiring only two fuel manifolds. The swirl-can modules would all be placed in the fan airstream, and would function as a pilot for the swirling core gases. No combustion-efficiency predictions can be made until the 3-D model is used; however, the swirl-can module design shows promise and will be pursued as part of the partial-swirl augmentor design as an alternative to the fan flameholders.

One design that combines the best features of both conventional and partial-swirl concepts would be to utilize only swirl-can modules downstream of a mixer nozzle. It is believed that swirl-can modules have only been tested once in an augmentor rig, and never at low inlet air temperatures. The technical risk of relying solely on swirl-can modules to achieve acceptable efficiencies at relatively low air temperatures is considered too high for this program, and this design was not studied further.

In conclusion, the best alternative to the conventional afterburner is the partial-swirl augmentor. Two different concepts of burning the fan air should be studied: (1) flameholders, and (2) NASA swirl-can modules.

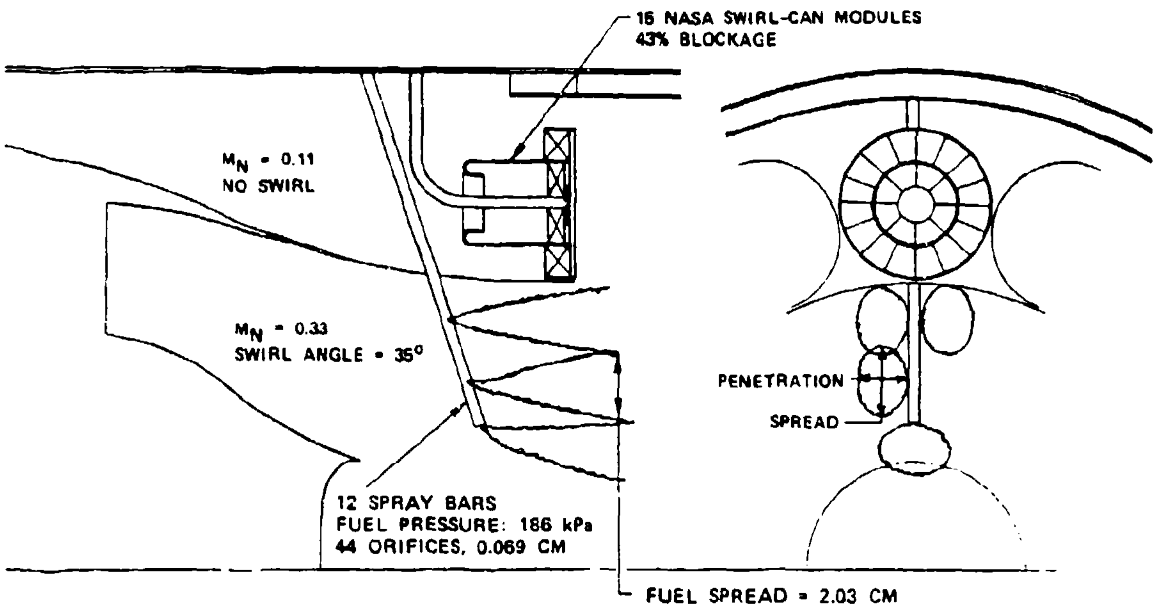


Figure 17. ETF Model 1050-15B Partial-Swirl Augmentor with NASA Swirl-Can Modules.

2.7 Augmented Engine Selection

The augmented engine performance data, given in Table 3, was generated from the predicted augmentor performance. The data has been declassified by making all performance relative. The engines with conventional augmentors have lower dry fuel consumption because of the mixer nozzle that is not part of the partial-swirl configurations. The effect of the mixer nozzle is to decrease the TSFC by 2.4 percent, but the partial-swirl augmentors have a lower pressure loss and a lower TSFC by 1 percent relative to a conventional, compound-nozzle augmentor. Therefore, the net difference in the dry TSFC for the conventional and partial-swirl augmented engines is 1.4 percent, if the effect of swirl in the engine exhaust nozzle is small. The low-bypass-ratio engine was shortened by 25.4 cm because of the higher efficiencies of the partial-swirl augmentor, but the high-bypass-ratio engine length was not shortened due to the relatively low efficiencies of the ETF Model 1050-7B augmentors. The diameter of the low-bypass-ratio engine is 7.1 cm less than the high-bypass-ratio engine with an afterburner, and 16.5 cm less with a duct burner.

The augmented engine performance listed in Table 3 was supplied to both GDC and MDAC. The results of the consultation with GDC are as follows:

- o Engine diameter is very critical and current engines are a tight fit. Also, the diameter must be limited in order that the missile will fit a standard torpedo tube, which eliminated the duct burner from consideration.

- o Approximately 1 percent of the mission is spent in the augmented mode for surface-to-air missile (SAM) avoidance, and therefore the augmented fuel consumption is relatively unimportant.

TABLE 3. AUGMENTED ENGINE PERFORMANCE.

Mach = 0.7 Sea-Level Std. Preliminary Installed Performance Data

Engine, ETF Model 1050	-15B		-7B		
Augmentor Type	Conv	Swirl	Conv	Swirl	Duct
Dry Performance					
Net Thrust, Relative	1.00	0.975	1.08	1.05	1.06
TSFC, Relative (1)	1.00	1.01	0.94	0.95	0.96
Airflow, kg/s	9.98	9.98	14.06	14.06	14.06
Augmented Performance					
Augmentation Ratio	2.0	2.0	2.0	2.0	2.0
TSFC, Relative (1)	1.00	1.03	1.09	1.02	1.08
Configuration					
Estimated Engine Weight, kg	120	116	132	132	138
Basic Turbofan Diameter, cm	33.0	33.0	36.3	36.3	36.3
Augmentor Diameter, cm	33.0	33.0	40.1	40.1	52.1
Basic Turbofan Length, cm (2)	59.2	59.2	59.2	59.2	59.2
Total Engine Length, cm (3)	153.7	119.4	154.9	154.9	119.4
Augmentor Length, cm (4)	68.6	43.2	68.6	68.6	63.5
Augmentor Efficiency, %	82	80	70	77	74

(1) JP-9 Fuel
(2) Fan Front Flange to L.P. Turbine E.G.V. Exit
(3) Fan Front Flange to Nozzle Throat
(4) Flameholder to Nozzle Exit

- Most GDC designs have vehicle configurations that result in relatively long exhaust ducts which can be used for the augmentor. The reason is that the engine is placed as far forward as possible to minimize boundary layer build-up.

- The high-bypass-ratio engine has a lower TSFC and requires less fuel to complete the mission. However, the high-bypass-ratio engine also has a larger engine diameter, which results in less fuel storage volume. The decrease in fuel requirements due to the lower TSFC for the high-bypass-ratio engine was calculated to be 41 kg for the GDC mission. However, the decrease in the amount of on-board fuel due to the increased engine-inlet diameter was calculated to be 36 to 48 kg, depending on the length of the flush engine inlet. Therefore, there is no advantage in range for the higher-bypass-ratio engine.

The MDAC mission requires a bypass ratio of 3.0 and a subsonic augmentation ratio of 3.0. Testing can be conducted to simulate the supersonic engine cycle in the augmentor rig if determined feasible.

The low-bypass-ratio (1.4) engine was selected as the most feasible augmented engine for the following reasons:

- It has a range equal to that of the high-bypass-ratio engine and has a smaller engine diameter.

- The engine is very similar to current engines being evaluated for future cruise missiles.

- Higher augmentor efficiencies can be achieved because of the higher augmentor inlet air temperature.

2.8 High-Density Fuel Study

The results of the study of JP-10, RJ-6, and carbon-slurry fuels are summarized in Table 4. The distillation temperatures are similar for JP-10, RJ-6, and conventional liquid fuels, and no adverse effect is anticipated. The mean droplet size will be 40-percent greater for RJ-6, but should be less than 60 microns (which is considered acceptable). The reduced hydrogen/carbon ratio will increase liner temperatures, but since the hot gases in contact with the liner are of low temperature because of the low fuel/air ratios, the liner temperature should remain within acceptable limits (1144K). The 2-D model has been modified to accept JP-10 and RJ-6. The models cannot handle carbon-slurry combustion; however, Garrett has measured a 77-percent efficiency with carbon slurry in a combustor with inlet temperatures and pressures nearly equal to that of the fan air in the present design study, (422K and 241kPa). The augmentor length for carbon slurry will be longer than required with other fuels, but acceptable efficiencies should be achievable. The fuel manifold, that is exposed to the hot core gases, will require substantial amounts of cooling air to prevent plugging the fuel orifices.

TABLE 4. HIGH-DENSITY FUEL STUDY

Fuel	Hydrogen/ Carbon Ratio	Mean Droplet Size Relative	Initial Boiling Temperature, K	90% Vaporization Temperature, K
JP-5	1.88	0.84	450	528
JP-9	1.54	1.00	380	541
JP-10	1.60	0.97	454	458
RJ-6	1.41	1.40	454	543

3.0 CONCLUSIONS

Of the several augmentor concepts screened, the conventional flameholder with mixer nozzle and the partial-swirl augmentor were selected as the two designs for detail analysis. The full-swirl augmentor was eliminated because of low combustion efficiency. The duct burner was eliminated because of its large increase in engine diameter. The partial-swirl augmentor can be greatly simplified by replacing the fan airstream flameholders with NASA swirl-can modules.

Of the two engines studied for their applicability to cruise missiles, the low-bypass-ratio (1.4) engine was selected for the following reasons: (1) the higher-bypass-ratio engine offers no range improvement, and the 1.4-bypass-ratio engine has a smaller diameter; (2) the chosen engine is similar to current engines being evaluated for future cruise missiles; and (3) the 1.4-bypass-ratio engine has higher inlet augmentor temperatures and is more suited for augmentation.

The impact of JP-10 and RJ-6 fuels will be small for these augmentor designs, but carbon-slurry fuel will require cooled fuel manifolds and longer afterburner lengths.

4.0 RECOMMENDATIONS

Based upon the preliminary design studies conducted in Phase I, it is recommended that a conventional and a partial-swirl afterburner be selected to be carried into final design definition. Both of these configurations utilize the Garrett ETF Model 1050-15B engine. The recommendation of these two concepts is based upon overall engine/mission system performance and engine/augmentor configuration requirements.

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